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I. M. Potravny, A. L. Novoselov, I. B. Gengut
Plekhanov Russian University of Economics (Moscow, Russian Federation; e-mail: ecoaudit@bk.ru)

FORMALIZATION OF THE GENERAL MODEL OF THE GREEN ECONOMY AT THE REGIONAL LEVEL[1]

The paper focuses on the study of the problems of the economic and mathematical modeling of the green economy at the regional level. The purpose of the research is the development of economic and mathematical tools for the economic and ecological systems' modeling at the regional level on the basis of the principles of green economy. The hypothesis of the research is based on the thesis that in the conditions of the exhaustion of natural resources and depletion of natural capital, the technogenic fields, production and consumption waste could be considered as a resource basis for modernization. Such factors' use leads to the elimination of accumulated environmental damage and substitution of natural resources. The paper describes the approaches to the system modeling problem-solving in order to develop the green economy both in the country and its regions. The urgency of the transition to a green economy is confirmed by the theoretical and practical research on the cyclical development of the socio-eco-economic systems. A number of formalized models and methods for solving the current environmental and economic issues including the economic valuation of accumulated environmental damage, eco-economic assessment of the efficiency of natural resource substitution with resource-substitute are proposed as well as the choice of an optimal set of resources-substitutes taking into account the financial and natural resource constraints. The authors research the typical model of green growth considering the exhaustion of natural resources, technogenic resources deposits involving in economic circulation through the implementation of investment projects on the elimination of accumulated environmental damage. The results could be used in the different regions of Russia for the justification and implementation of investment projects within the framework of the federal target program "Elimination of accumulated environmental damage" in 2015–2026 years.

Keywords: green economy, evaluation of accumulated environmental damage, natural food chain, substitution of mineral resources, non-linear programming, sustainable development, regional aspects, resource depletion, environmental damage accumulated, efficiency

Introduction. The development backgrounds of a green economy's formalized model

United Nations Environment Programme (UNEP) considers that green economy improves human well-being, ensures social justice and reduces environmental risks and its degradation[2]. In the broadest sense, the green economy provides low emissions of greenhouse gasses, efficiently uses resources and serves the interests of the whole society. In the scientific literature, the "green" economy concept also determines the economy, which increases and recovers natural capital. Many countries use different tools of a green economy in national policy and their development strategies. The need for green economy development is recognized in many countries including Russia. At the same time, many developing countries fear that the use of the green economy model can slow down their development process.

The world's population growth leads to increasing of the non-renewable natural resources production and use, for example, over the past one hundred years, the consumption of mineral resources has increased 15 times. The structure of resources consumption has been significantly changing by decade; the new types of fuel and energy resources are involved in agricultural land use [1, 2]. At the beginning of the XXI century, the global oil consumption's share reached 40 %, coal — 27 %, natural gas — 23 %; the share of nuclear power, hydropower, solar and wind accounted for 10 %. In the 50–60-s of the 20th century, the peak of coal consumption has been passed [3]. Since the 80-s of the last century, the growth rate of oil consumption decreased significantly [4]. The forecasts of the Organization for Economic Cooperation and Development show that the current modes of production and consumption

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[2] Towards a green economy: pathways to sustainable development and poverty eradication. Synthesis report for decision-makers // UNEP, 2011. 43 p. [Electronic resource]. URL: www.unep.org/greeneconomy (date of access: 05.08.2015)

by 2050 compared with the beginning of the 21st century the world may lose two-thirds (61 to 72 %) of flora and fauna and the natural areas preservation may be irreversibly violated by 7.5 million km^2, which is comparable to the territory of Australia. According to I. Wallerstein, the absolute population growth, the volume indices of production and wealth over the past 40 years might be the same as for the 400 years prior to 1945 [5]. Herewith, the process of natural resource use conforms to the logistic curve. [6].

According to the experts of the International Energy Agency (IEA), due to expected world consumption growth up to 2030, there is a strong need to find oil deposits in six times larger than the total reserves of Saudi Arabia. As a result of a comprehensive study, more than 800 oil deposits, containing 75 % of the world reserves are depleted. Most deposits have already passed peak production values. In these circumstances, the question of green economy's general model formalization taking into account regional specificities becomes more and more important [7, 8].

Formulation of the problem. Macroeconomic model of resource depletion and transition to a new economy

The above facts confirm the validity of the forecast of M. Hubbert, refined with the help of a mathematical model of J. Lere [9] on the depletion of mineral resources. Verhulst curve (1) is used as the basis of this model [10], which may be represented by the following relationship:

$$Q_t = \frac{U}{1 + \exp\left[-b\left(t - t_m\right)\right]}, \tag{1}$$

where Q_t — cumulative production at a time t; t — years; U — cumulative recoverable reserves; t_m — peak point; b — a factor that describes the slope of the (production growth rate). Note that at a later stage $t > t_m$, when production growth is negative, i. e. there is a decline in annual production, production growth rate remains positive.

Researchers at the Swedish Lund University have developed a new model of the world[3], showing the depletion of the planet's resources. According to their forecasts, the first iron production will peak in 2030, and the secondary peak will be in 2060 in response to higher prices and the consequences of the global recession. Then iron can become a scarce resource. The gold production passed the peak in 2000. The deficit onset is predicted up to 2070-ies. The platinum group metals' peak occurs in 2020-s., for lead, silver, zinc, it is expected about 2030; for copper, chromium, nickel, molybdenum, the depletion occurs after consumption peak during 2040–2050. The peak production of phosphate was passed in 2010. The time of the phosphorus deficiency onset could be possible in critical point — in 2040.

In 2002–2010, raw Index DJ-UBS (currently — Bloomberg Commodity) increased by 328 %. As a result, there was a structural shift in the global economic growth model, and the prices of almost all commodities at the beginning of the century were at the bottom of the cycle. The model, in which China played the role of "world factory", but developed countries provided growth due to consumer demand, is replaced by another one: the production and final consumption will be more evenly distributed across the globe [11, 12].

Along with models of mineral resources depletion, it should pay attention to the theory of three cycles (Kondratiev, Juglar and Kitchin) and also a theory proposed by Joseph Schumpeter. According to this approach, the final curve of economic development can be represented as a sum of oscillatory processes with different frequency relatively to trend trajectory of the development, which is called the "grand unification". The negative trends' imposition of these cycles occurred during the Great Depression. Recent studies confirm and clarify the periods of considerate cycles [13, 14]. The calculations of experts, engaged a great while in the study of long waves [15–17] show that the depression will last until 2017–2018, then there will be a rise according to the 6th technological way in the period from 2018 to 2040 (Table 1).

Practical efforts for the sixth technological way transition and green economy

At the turn to the sixth "great cycle", the concept of a green economy has been introduced and its most important task is the natural resources exhaustion problem-solving. Among the reasons for the non-traditional energy sources engaging in economic activities [18–20], we can highlight the decisive:

[3] Retrieved from: https://goldenfront.ru/articles/view/nashim-vnukam-tochno-ne-hvatit (Date of access: 05.08.2015).

Table 1

"Great cycles" and technological ways

Number of cycles	Period, years		Technological ways
	Beginning	Ending	
1	1803	1841–1843	textile factories, the industrial use of coal
2	1844–1851	1890–1896	coal mining and ferrous metallurgy, railway construction, the steam engine
3	1891–1896	1945–1947	heavy engineering, power engineering, inorganic chemistry, steel and electric motors
4	1945–1947	1981–1983	production of cars and other machinery, chemical industry, oil and internal combustion engines, the mass production
5	1981–1983	~2018	development of electronics, robotics, computing, laser technology and telecommunications;
6	~2018	~2060	presumably, NBIC convergence (convergence of nano-, bio-, information and cognitive technologies)

Source: Akaev, A. A. (2009). Sovremennyy finansovo-ekonomichesky krizis v svete teorii innovatsionno-tekhnologicheskogo razvitiya ekonomiki i upravleniya innovatsionnym protsessom [Modern financial-economic crises in the innovative and technological development theory of the economy and innovative process management]. Sistemnyy monitoring. Globalnoye i regionalnoye razvitie [System monitoring. Global and regional development].Moscow: URCC Publ., 141–162; Korotaev, A. V. & Tzirel, S. V. (2009). Kondratyevskie volny v mirovoy ekonomicheskoy dinamike [Kondratiev waves in world economic dynamic]. Sistemnyy monitoring. Globalnoye i regionalnoye razvitie [System monitoring. Global and regional development]. In: D. A. Khalturin, A. V. Korotaev (Eds). Moscow: URSS Publ., 189–229.

— the growth of the costs and prices of the traditional energy resources [18];
— the proven reserves reduction of natural resources [15];
— the need for disposal of accumulated waste with the greatest benefit.

The basis of price movements on exhaustible natural resources is based upon the Hotelling rule: the most socially and economically profitable extraction path of non-renewable resource is one along which the price of the resource, determined by the marginal net revenue from the sale of the resource, increases at the rate of interest. [21, 22]. Despite prices fluctuations, which inevitably arise under the influence of non-market factors, the general prices' dynamics show their growth for all types of exhaustible natural resources. According to data and the long-term forecasts[4], the world crude oil price may be from 50 to 200 USD / bbl in 2030 with an average assessment of 125 USD / bbl. The international research community supposes that the first in the natural resources' substitution queue is oil. The green economy development programs realized by many countries should be mentioned as their practical steps to address the problem. For example, the Swedish Government realizes the policy on complete abandonment of hydrocarbon fuel and the deliverance of the country from dependence on oil (oil-free nation) until 2020[5]. Brazil plans to produce 80 % of transport biofuels from sugar cane. In Japan, "Low-carbon society action program" is formed and its the most important indicator is carbon emissions' reduction. In the United States, the National Program for Energy Conservation (National Action Plan for Energy Efficiency) is implemented. The Plan "Clean Energy" adopted in the US in 2015 aims to reduce greenhouse gas emissions by power plants nearly a third during the next 15 years, and provides the alternative energy development mainly solar and wind. In China, at the official level, the low-carbon economy was announced as the main strategic objective of the country taking the advantages of the future economy.

System of tasks for the increase of green economy's efficiency

The leading world countries' actions listed below should be considered as useful. [23] However, their concepts and programs are based on the documents which are too political. For balanced policy development seeing the transition to a green economy, it is necessary to establish formal criteria for evaluating and building a system of economic and mathematical models to carry out the environmental-economic analysis of the current situation, to determine the optimal management decisions and to choose the best options for their implementation. The figure shows a general view of

[4] World Energy Outlook 2011. Are We Entering a Golden Age of Gas? International Energy Agency. Retrieved from: http://www.worldenergyoutlook.org/goldenageofgas/ (date of access: 21.08.2015); IEA World Energy Outlook 2008. Alternative Policy Scenario. Retrieved from: http://www.ren21.net/Portals/0/GFR_Scenario_Profiles_draft_Jan16.pdf (Date of access: 12.08.2015).

[5] See http://geosfera.info/evropa/shveciya/208-shveciya-zelenaya-yekonomika.html (date of access: 12.08.2015)

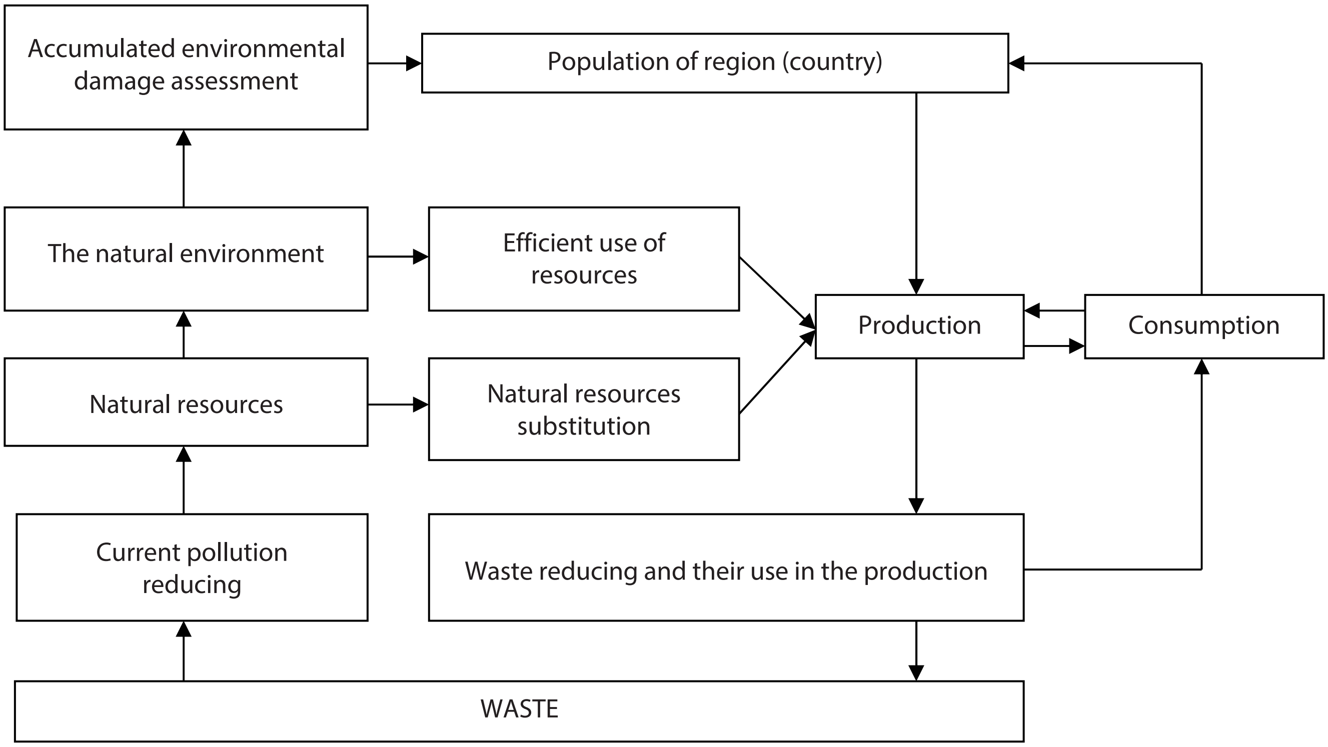

Fig. *Natural-product model with the main tasks of green economy development*

the natural-product model, where the economic and production processes but also the population of the region (country) are performed in rectangles; the material and labor flows are represented by the arrows.

The design of criteria for evaluating green economy development is the main task of the natural-product model. The basic mathematical tasks which should be posed and solved in order to move towards a green economy are also performed in this model.

Currently, in Russia, there are 10 resources' segments of the investment in the natural resources and environmental protection. Among them, there are agriculture, forestry, water, fishery, housing, energy, industry, tourism, transportation, disposal and recycling. However, in many countries, the energy is seen as a green growth point of the national economy as a whole. It is primarily due to the depletion of hydrocarbon resources and greenhouse gas emissions. In the energy sector, a green economy involves the use of energy-efficient technologies as well as environmentally friendly low-carbon energy sources and supposes alternative energy development. The problem-solving aims for natural resources' efficient use and the substitution of exhaustible natural resources by resource-substitutes.

The economic activity has led to the pollution accumulation—past damage. It is proved to be so great now that since last quarter of the 20 century, the governments of the developed countries have begun works on the elimination of the accumulated pollution. In 1980, in the US, the Law on the adoption of comprehensive measures for environmental protection, compensation and responsibility (CERCLA—Comprehensive Environmental Response, Compensation, and Liability Act[6]) was adopted. As a result of this Act, Superfund was created to eliminate the environmental problems of the past damage (e.g. the elimination of the previous damage of the Great Lakes). In 2011, the Russian Ministry of Natural Resources selected 194 primary regions where the accumulated environmental damage must be eliminated. There is also the federal target program "Elimination of accumulated environmental damage" in the 2014–2025. In Russia, the pilot project on Franz Josef Land's accumulated damage elimination is implemented. However, the guidelines on the economic evaluation of accumulated damage haven't been still developed. The scarce natural resources' substitution by resource-substitutes requires the creation of complex models, which will allow to assess the economic feasibility of substitution and to find the best options for their use. Look at this problem in more detail.

[6] Retrieved from: http://ecodelo.org/o_nakoplennom_ekologicheskom_ushcherbe_i_potentsiale_v_baikalskom_regioneproblemy_i_vozmozhnosti_lik (Date of access: 05.08.2015).

Criteria for green economy development

The analysis of sustainable development at the country level is currently based on the indicators for the analysis and the forecast of the environmental situation. Most of the international organizations (UN, World Bank, Organization for Economic Cooperation and Development, the European Economic Community etc.) and developed countries have their own systems of the sustainable development indicators. [24, 25] To assess the effectiveness of the executive authorities of the Russian Federation, in 2007, the system of 43 basic and 39 additional indicators characterizing the level of socio-economic development of the region has developed. In the same year, the Ministry of Economy and Trade of the Russian Federation prepared a list of same indicators for public authorities of the Russian Federation, which included more than 130 indicators [17, 18]. The indicators which can be used at the regional level are presented in sources [28, 29].

Using a system of indicators for comparison and analysis is rather difficult cause of large dimension. From this point of view, the cost parameters perform a great interest. The first among them is "debt-for-nature" developed by Professor K. Gofman (CEMI). The Environment and Resources Protection Committee of China has been developed the green GDP index, which is calculated since 2004. The World Bank and the United Nations carried out aggregated search criteria which are based on the measurement value. One of the criteria proposed by the UN Statistics Division is Environmental adjusted net domestic product (*EDP*), which is defined by the formula (2):

$$EDP = (NDP - DPNA) - DGNA, \tag{2}$$

where the *NDP*—net domestic product; *DPNA*—the valuation of depletion of natural resources; *DGNA*—the valuation of environmental damage.

The World Bank developed a more interesting figure—the real savings (*GS*—genuine (domestic) savings):

$$GS = (GDS - CFC) + EDE - DPNR - DMGE, \tag{3}$$

where *GDS*—gross domestic savings; *CFC*—the value of depreciation of produced assets; *EDE*—spending on education; *DPNR*—the depletion of the value of natural resources; *DMGE*—the pollution damage. The last of the examined indicators (3) can be used as a criterion of the global transition to a green economy. This figure can be represented as a vector of the optimality criterion, if you divide the economic and natural resource components and treat them as equivalent criteria:

$$\begin{cases} f_1 = (GDS - CFS) + EDE \to \max, \\ f_2 = DPNR + DMGE \to \min. \end{cases} \tag{4}$$

The use of the vector criterion (4) lets to find compromise solutions on the Pareto for a balanced transition to a green economy.

The economic evaluation model of the past (accumulated) environment damage due to the pollution

The two factors (geophysical and economic) simultaneously influence on the accumulated damage value. Geophysical factors or adsorption (carrying capacity) is a natural resource of the environment. The absorption reflects the ability of the natural territory or water area without self-destruction and the loss of the stability to degrade natural and anthropogenic substances and to eliminate their harmful effects. At the same time, in addition to a permanent damage reduction an opposite effect occurs due to economic factors. As the economic damage assessment is considered, the current values of the damages cause of inflationary processes constantly increase over time. Simultaneously, there are two different processes, one of which increases the accumulated environmental damage, and the other—reduced it [20].

Thus, taking into account the absorption and inflation, the amount of accumulated environmental damage can be calculated as follows [20]:

$$Dm_t = \sum_{\tau=t}^{T} (Dm_{\tau(t)} \times a^{\tau-t} \times (1+r)^{T-\tau}), \tag{5}$$

where Dm_t—caused damage over the year *t*, taking into account the reduced impact on the absorption of its value and inflation to end the year *T*; $Dm_{\tau(t)}$—the value of the accumulation of damage, calculated in the framework of the year t for each subsequent point in time τ; a—absorption coefficient (carrying capacity); r—the discount rate (the refinancing rate equal to the bank of the year); t—year in the period of accumulation of damage $t=\overline{t_0,T}$; τ—the period within the year t, $\tau=\overline{t,T}$; t_0 — year, assumed for the original (with which began to accumulate damage); T—year, assumed for the final (the last for which damages are calculated).

To obtain the final value of accumulated environmental damage for all years t (since year t_0 till year T) it is necessary to sum accumulated environmental damage at each time point (5) for all years

$$Dm_{accum.}=\sum_{t=t_0}^{T}Dm_t.$$

The total amount of accumulated environmental damage as a result of past economic activity for all considered years can be calculated using the formula:

$$Dm_{accum.}=\sum_{t=t_0}^{T}\sum_{\tau=t}^{T}(Dm_{\tau(t)}\times a^{\tau-t}\times(1+r)^{T-\tau}). \tag{6}$$

This method of economic evaluation of the past damage (6) was first used in practice during the realization of the federal target program “Social and environmental rehabilitation of territories and public health of Chapaevsk” (Samara region, 1996). In 2013, the same method was used to assess the cumulative environmental damage for the islands of the Franz Josef Land. During the federal programme and project development realization, the sources’ elimination of the negative impact of the damaged areas was assessed. The approbation demonstrated the practical suitability of the economic evaluation method for the accumulated environmental damage for development and ecological-economic substantiation of federal and regional programs in Russia. In particular, this approach was used for the study and implementation of investment projects of the federal target program “Elimination of accumulated environmental damage” in the 2015–2026.

The economic evaluation model of the natural resources’ substitution effectiveness

The resources substitution in the production process leads to a change in a set of economic, environmental and social factors. In economics, it means the changes in costs and, consequently, prices. In the field of ecology, the resources’ substitution brings to damage due to the pollution during extraction, production and disposal. The social perception of resources’ substitution is complicated by inertia and includes an image aspect: the use of a substitute is treated as the lower class products. At the same time, the consumers are interested in lower prices that could be achieved through the products of substitutes.

Table 2 presents the natural-product vertical for traditional production based on the natural resources extraction (e.g. oil). Natural-food chain expanded to the disclosure of the factors that ensure damage (costs) and gains on three sides—the natural environment, the final products’ consumers and produces implementing the mining and production of natural raw materials until a final product. The factors affecting the damage (costs) and benefits in the given natural-product vertical change their value during substituting natural resource. Moreover, new factors and new stakeholders may appear as a consequence of the natural resources substitution by another kind of resource including artificial analog.

Table 2

Structuring of the natural-product vertical in the traditional approach

Loss factor (cost) $j = 1, n_j$			**Element of natural-product vertical, $k = 1, n_k$**	**Benefit factor, $i = 1, n_i$**		
Natural environment	**Consumer**	**Producer**		**Natural environment**	**Consumer**	**Producer**
Damage	Recycling costs	Recycling costs	Products recycling	Environmental preservation	The use of recreational potential	—
Drain on resources; damage	Operation costs	—	Product use	—	Benefits use	—
Drain on resources; damage	—	Production costs	Production	—	—	Products’ sale
Drain on resources; damage	—	Extraction costs	Extraction or use natural capital	—	—	Resource’s sale

Indexes listed in Table 2 ($j = 1, n_j$; $k = 1, n_k$; $i = 1, n_i$) allow to present a comprehensive effectiveness assessment of the natural-product vertical implementation. If the costs (damages) j-th for the k-th element of natural-food vertical are marked Z_{kj}; the benefits of i-th indicator for the k-th element of natural-product vertical indicate P_{ki}, the comprehensive evaluation of the effectiveness with considering time factor will be calculated by the formula:

$$NPV = \sum_{t=1}^{T}\left[\sum_{k=1}^{n_k}\left(\sum_{i=1}^{n_i}P_{ki} - \sum_{j=1}^{n_j}Z_{kj}\right)\right]\left(1+r\right)^{1-t}. \qquad (7)$$

Formula (7) is the basis for evaluating the economic efficiency of natural-product vertical. If the existing version of natural resources use and the substitute resource are compared, it should pre-assess the changing costs (damage) ΔZ_{kj} and benefits ΔP_{ki}, then the substitution will be assessed by the formula (8):

$$NPV = \sum_{t=1}^{T}\left[\sum_{k=1}^{n_k}\left(\sum_{i=1}^{n_i}\Delta P_{ki} - \sum_{j=1}^{n_j}\Delta Z_{kj}\right)\right]\left(1+r\right)^{1-t}. \qquad (8)$$

The increase of the prices and costs of the extraction and production of natural resources, the mismatch of the volume of the production needs of the economy, the availability of opportunities to meet the needs of the resource by the resource-substitute, all these factors influence on the process of substitution of natural resources [31]. In general terms, if NPV_1—the net present value of resource-substitute, and NPV_0—the net present value of the mining (exploitation) of natural resources, the condition of the economic expediency of natural resource substitution by resource-substitute should be written in the form $E = NPV_1 - NPV_0 > 0$ [32].

In order to analyze the impact of external and internal factors on the economic expediency of the natural resources substitution, it should be recommended to use the model of the efficiency decomposition of the resource substitution on factors without a trace. Also, the method of chain substitutions, the method of complete permutations or logarithmic method could be used for problem-solving [33].

The evaluation model of the technological feasibility of the substitution of natural resources

In the condition of the substitution effectiveness of natural resources considered above, the technological feasibility of substitution hasn't been taken into account. In such circumstances, an assessment of environmental and economic efficiency is expediently carried out with the real options use (ROV—Real Option Value). For the calculation, the European option-call should be used because the horizon of the calculation with traditional and replacement options is the same and equals to T. Wherein a net present value of the use of substitute natural resource as an extension option can be considered. [22]

Option value is calculated as follows: $ROV_i = NPV_i^{\exp} - NPV_0$, where $NPV_i^{\exp}$—expected value, which is calculated according to the formula of Hurwitz (9):

$$NPV_i^{\exp} = \lambda \times NPV_i + \left(1-\lambda\right) \times NPV_0. \qquad (9)$$

It is expediently to realize training programs and resource substitution through such natural gas substitute variants implementation for which at least the option value is greater than zero, i.e. $NPV_i^{\exp} > 0$.

The model of the optimal substitution of natural resource

We offer the general model of optimal choice the substitution of for natural resources in volume P^0 by several alternatives $i = 1, 2, \ldots, n$, each of them to substitute a scarce resource in volume P_i. As far as in general case $P_i < P^0$, it is necessary to generate an optimal set of substitute resources types. For such choice, the sought-for variable U_i taking value 1 must be used if the i-th resource-substitute are chosen to replace scarce natural resources, or it takes 0 if the i-th resource-substitute is not selected to substitute scarce natural resource. Then the restriction on the substitution of natural resources in its full amount will be:

$$\sum_{i=1}^{n} P_i U_i \geq P^0. \qquad (10)$$

Because the funding for the projects of the substitution of scarce natural resources are limited and equals to B, the costs of the i-th project implementing are Z_i, the restriction on financing can be explained as follows:

$$\sum_{i=1}^{n} Z_i\, U_i \le B. \tag{11}$$

As far as the natural resources substitution projects may require additional land resources (e.g. wind and solar power leads to the land withdrawal from economic turnover), the limit on marginal withdrawal of land resources in the amount of S^0 can be requested:

$$\sum_{i=1}^{n} S_i\, U_i \le S^0. \tag{12}$$

The restriction on the limiting value of the economic assessment of environmental damage Y^0 in the substitution project implementation can be taken into account, if during the implementation of the i-th project the economic assessment of environmental damage is Y_i, and the economic assessment of environmental damage due to extraction of natural resources substitution is Y^1:

$$\sum_{i=1}^{n} Y_i\, U_i \le Y^0 - Y^1. \tag{13}$$

If to search for the optimal set of substitution options (projects) by the criterion of maximizing the net present value (*NPV*), the objective function of the task will be:

$$F(U) = \sum_{i=1}^{n} NPV_i\, U_i \to \max. \tag{14}$$

As a result according to calculations 10—14, the variant of the substitution of natural resources by a set of several types of resources (projects), which will provide maximum profits on the calculating horizon of net present value (*NPV*) will be obtained. However, the intention to a green economy requires an equivalent account of the economic and environmental interests. To do this, in optimal model selection the substitution projects of natural resources, it is expedient to optimize two criteria: economic $F_1(U)$ (the total profit or net present value maximizing) and environmental $F_2(U)$ (the total environmental damage minimizing):

$$F_1(U) = \sum_{i=1}^{n} NPV_i\, U_i \to \max \tag{15}$$

and

$$F_2(U) = \sum_{i=1}^{n} Y_i\, U_i \to \min. \tag{16}$$

If there are restrictions considered previously except the restrictions for marginal damage to the environment:

$$\sum_{i=1}^{n} Z_i\, U_i \le B, \tag{17}$$

$$\sum_{i=1}^{n} P_i\, U_i \ge P^0, \tag{18}$$

$$\sum_{i=1}^{n} S_i\, U_i \le S^0. \tag{19}$$

In the environmental criterion (16), it is expedient to add the depletion component of natural resources as a part of the economic evaluation of damage to the environment particularly for land resources:

$$F_2(U) = \sum_{i=1}^{n} (Y_i + CS_i) U_i \to \min. \tag{20}$$

The accounting of natural resource and environmental components will be more complete when their sum (20) will be correlated with the volume of resources that are substituted by the selected projects:

$$F_2(U)=\frac{\sum_{i=1}^{n}(Y_i+CS_i)U_i}{\sum_{i=1}^{n}P_iU_i}\to \min. \tag{21}$$

The result is a multi-criteria optimization task with a linear (20) and a linear fractional (21) criteria. For the problem-solving, first of all, it is necessary to carry out criteria scaling, i.e. to bring them to one dimension, one direction optimization and unified range of changes. The criteria scaling can be carried out using the following transformation:

$$\omega_l(U)=\begin{cases}\dfrac{F_l^{\max}-F_l(U)}{F_l^{\max}-F_l^{\min}}, l\in L^{\max},\\[2mm] \dfrac{F_l(U)-F_l^{\min}}{F_l^{\max}-F_l^{\min}}, l\in L^{\min},\end{cases} \tag{22}$$

where $L^{\max}$ ($L^{\min}$) — set of maximizing (minimizing) criteria; $F_l^{\max}$ ($F_l^{\min}$) — maximum (minimum) value of the l-th criterion within the feasible solutions area formed by the above restrictions.

The determination $F_l^{\max}$ and $F_l^{\min}$ of the values for the criteria $l\in L=L^{\max}\cup L^{\min}$ should be carried out on the basis of the local optimization problem-solving, regardless of the economic content of the criteria. The local optimization of the problem-solving can be obtained by the method of Balash, Lemke and Shpilberg method [34] or the method of random managed search Piatetsky-Shapiro; methods of Volkonsky, Levin and Pomansky [35].

Multi-criteria optimization should lead to the solution on the Pareto compromise decision. In order to find the solution, it is required to carry out the convolution of the scaled criteria on the basis of equitable concession of Chebyshev's principle:

$$\max\{\omega_1(U);\omega_2(U)\}\to \min. \tag{23}$$

Target minimax function (23) implementing the principle of Chebyshev's equitable concessions guarantees solutions of Pareto compromise. The following condition will be achieved: $\omega_1(U)=\omega_2(U)+\delta$ where $|\delta|>0$ — the maximum possible accuracy, which the condition will be realized with Boolean variables. For numerical solution, it is necessary to move from a minimax objective function to form corresponding mathematical programming problem. For this purpose, it should be introduced a variable V, which is maximum deviate from the local optimum criteria:

$$V=\max\{\omega_1(U);\omega_2(U)\}. \tag{24}$$

Then, it is possible to compose a nonlinear programming task (25–30) with Boolean variables equivalent to the criteria convolution written above:

$$V\to \min, \tag{25}$$

$$V\ge \omega_l(U),\ l\in L=L^{\max}\cup L^{\min}, \tag{26}$$

$$\sum_{i=1}^{n}Z_iU_i\le B, \tag{27}$$

$$\sum_{i=1}^{n}S_iU_i\le S^0, \tag{28}$$

$$\sum_{i=1}^{n}P_iU_i\ge P^0, \tag{29}$$

$$U_i=\begin{cases}1,\\ 0,\ i=1,2,\dots,n\end{cases} \tag{30}$$

To find the solutions for task 25–30, it should use a modification of the method of contracting simplex [36] in the relation to the specificities of the vector optimization task with Boolean variables. The method offers to find the optimal value function V^* in the interval between zero and one by bisect the segment.

It should be noted that if $V = 1$ the limits system is always joint and at $V = 0$ it is notoriously inconsistent. Indeed, if a value of $V = 0$, i.e. when all the criteria take the optimal value, the system of restrictions would be compatible and the resources would be enough to meet the best way all the objectives of its development, the question of a compromise between these criteria wouldn't stand. This situation contradicts to the economic sense of the problem.

The bisection method realized for the problem-solving at initial iteration $k = 0$, we can suppose that $V_0^c = 1$ and $V_0^n = 0$ (in the future indices c indicate such values V_k, which the limits' system is consistent with, and indices n perform conditions when the limits' system is inconsistent). New value V_k at iteration k is determined by the formula (31):

$$V_k = \left(V_{k-1}^c - V_{k-1}^n\right) / 2. \tag{31}$$

Then the index marking the resulting value V_k is determined by the simplex method. The variable with opposite index at iteration k gets the same value that it had at the previous iteration. The search process continues until the condition is not satisfied (32):

$$\left|V_{k-1}^c - V_k^c\right| \le \xi, \tag{32}$$

where ξ — given accuracy of calculation, $\xi > 0$.

Conclusion

The models and methods presented in the paper allow normalizing the most important problem of assessment, analysis and planning of the transition to a v"green" economy. Nowadays, the researchers of the Plekhanov Russian University of Economics work on the choice of the problem-solving of development strategies aiming at a "green" economy both at the federal and regional levels taking into account the ecological and economic risks [37], the forecast of social, environmental and economic consequences of the use of resource-substitute considering the scarcity growth of natural resources, the changes of the price of natural resources and other factors.

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Authors

Ivan Mikhaylovich Potravny — Doctor of Economics, Professor, Department of Management of Projects and Programs, Plekhanov Russian University of Economics (36, Stremyanny per., Moscow, 117997, Russian Federation; e-mail: ecoaudit@bk.ru).

Andrey Leonidovich Novoselov — Doctor of Economics, Professor, Department of Mathematical Methods in Economics, Plekhanov Russian University of Economics (36, Stremyanny per., Moscow, 117997, Russian Federation; e-mail: alnov2004@yandex.ru).

Igor Borisovich Gengut — PhD in Economics, Postdoctoral Candidate, Department of Management of Projects and Programs, Plekhanov Russian University of Economics (36, Stremyanny per., Moscow, 117997, Russian Federation; e-mail: igengut@gmail.com).